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ABSTRACT

Information on equipment and techniques that school facility personnel may use to evaluate IAQ conditions are discussed. Focus is placed on the IAQ parameters of air flow, air temperature, relative humidity, as well as carbon dioxide and the equipment used to measure these factors. Reasons for measurement and for when the measurement of these parameters is warranted, along with guidance for the interpretation of the data obtained, are covered. This is followed by an overview of equipment types that are available to quantify the specific parameters, and a comparison table presenting key factors that differentiate the types of equipment available. Various measurement techniques, such as measuring a room's air velocity, are summarized along with the methodologies recommended for obtaining useful data. Some of the common problems encountered when measuring IAQ are described. It is claimed that with a good understanding of the dynamics of the key IAQ parameters and a modest investment in monitoring equipment, school facilities staff can provide quick, cost-effective responses to IAQ complaints and establish a program that can identify potential IAQ problem areas. (Contains 5 tables and 10 references.) (RJM)

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EQUIPMENT FOR MEASURING AIR FLOW, AIR TEMPERATURE, RELATIVE HUMIDITY, AND CARBON DIOXIDE IN SCHOOLS

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June 1996
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Introduction

The purpose of this bulletin is to provide information on equipment and techniques that may be appropriate for use by school facility personnel to evaluate indoor air quality (IAQ) conditions. While there are times when it is necessary to obtain the services of a consultant, there are many instances where IAQ problems may be diagnosed through measurements obtained with relatively low cost, easy-to-use instruments. The IAQ parameters chosen for discussion in this bulletin are air flow, air temperature, relative humidity, and carbon dioxide.

Each of the four IAQ parameters are presented in more detail in following sections of the bulletin. Each section will include:

- Reasons for measurement - discusses when measurement of the parameter is warranted, and guidance for the interpretation of the data obtained.
- Equipment types - provides an overview of the different types of equipment that are available to quantify the specific parameter.
- Comparison table - presents key factors that differentiate the types of equipment available.
- Measurement techniques - presents and summarizes the methodologies recommended for obtaining useful data.
- Common problems encountered - provides information concerning potential sources of error that may invalidate the data being collected.

A number of factors may serve to differentiate one monitoring instrument or device from another. **Table 1** provides an overview of these selection factors. The following definitions are provided to assist in understanding some of the common performance specifications that are provided by instrument manufacturers.

1. Range - the minimum and maximum measurement limits of an instrument.
2. Full scale - the maximum measuring limit for a given range.
3. Sensitivity - the minimum value that can be detected for the parameter.
4. Interference - an undesired positive or negative response caused by a parameter other than the one being measured.
5. Accuracy - the degree of agreement between a measured value and a true value, usually expressed as ± percent of full scale.
6. Precision - the degree of agreement between repeated measurements of the same concentration.
7. Response time - the time interval from a change presented to the instrument to a reading of 90% of the ultimate recorded concentration.
8. Zero drift - the change in instrument output over a stated time of unadjusted continuous operation, when the input value is zero (usually expressed as percent of full scale).
9. Span - the uppermost concentration of a pollutant set to be displayed on an instrument's output.
10. Span drift - the change in instrument output over a stated time of unadjusted continuous operation, when the input value is a specified positive value (usually expressed as a percent of the input value).

The "comparison tables" presented in this bulletin will not detail every operating and performance specification for the instrument types, but will note those that are typical for a specific instrument type and/or cost range and provide notes on other key factors.

Table 1. Factors to Consider When Choosing Equipment

Factors	Variables
Operating Specifications	Size, weight, power source requirements (incl. battery life).
Performance Specifications	Accuracy, precision, range, detection limits, interferences, drift.
Costs	Initial cost; cost of ongoing operation, calibration, and maintenance.
Versatility	Type of readout, time averaging capability, data storage and retrieval options, ability to generate reports/graphs, ability to monitor additional parameters.
Ease of Use	Ruggedness, time requirements, level of expertise needed.

Air Flow

Reasons for Measurement

The proper movement of air within an occupied indoor environment is essential for comfort and for the dispersal/removal of pollutants. The majority of IAQ investigations can benefit greatly from gathering data on air flow. Measurements of HVAC system air flows allow the investigator to check the system performance against design specifications (if known), and against industry standards (e.g., American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE), Standard 62, "Ventilation for Acceptable Indoor Air Quality". The measurement and/or visualization of air flow within the general area or within a "microenvironment" (e.g., at a workstation) permits the investigator to evaluate the effect of air movement on comfort (too little movement – stagnant air, too much movement – drafts), to determine if the air being provided to the space reaches the occupants and pollutant sources (also known as proper air mixing), and to identify air movement patterns, or pathways, whereby contaminants may be transported from the point of generation to another area. Air movement can be quantified directly with instruments that sense the movement of the air, or with devices that measure the positive and negative pressures that cause the air to move.

Equipment Types

A wide variety of equipment is available to help the IAQ investigator assess air flows. These may be classified as flow visualization, flow measurement, and pressure sensing devices. Flow visualization devices such as "guns," sticks, bottles, and tubes are mechanisms for releasing chemical smokes. These "smokes" include acid vapors formed from the release of titanium tetrachloride, stannic chloride, and zinc stearate powder. Sulfuric and hydrochloric acid vapors are extremely irritating. All chemical smokes should not be used in the direct vicinity of building occupants.

The types of flow measuring devices are flow hoods, vane anemometers, and thermoanemometers.

Flow hoods incorporate fabric and metal frame hoods of different sizes to direct the entire air flow at a supply or exhaust opening to an array of air velocity sensors that automatically averages the flow and provides a direct readout of total flow in cubic feet per minute (cfm).

Table 2. Comparison of Air Flow Equipment

Type	Range	Accuracy	Price	Comments
Chemical Smoke	Velocities < 150 fpm	NA	$50-100 (refills $12-50)	Extremely useful. Smoke is corrosive and irritating, do not use in direct vicinity of occupants. Can cause smoke detectors to alarm.
Flow Hoods	50-2,000 cfm 0-1,400 cfm	± 3% ± 5%	$2,300-2,900 $1,300	Little field maintenance required. Periodic laboratory calibration required. Must purchase various sized hoods to measure flows at vents with varying dimensions.
Rotating Vane Anemometers	200-3,000 fpm (mechanical) 25-10,000 fpm (electrical)	± 1% ± 2% ± 3%	$799 $189-555 $155	Requires frequent calibration. Not very rugged.
Swinging Vane Anemometers	50-10,000 fpm 50- 2,500 fpm	± 2% ± 5%	$1,075 $275	Allows for pressure readings and includes various probes for numerous applications. Limited applications. Both require frequent calibration.
Thermo-anemometers	10-10,000 fpm	± 2-3% ± 5%	$500-1,200 $399	Many include air temperature monitoring capabilities. Some offer data storage and optional printing. All require frequent calibration. Requires battery power.
Pitot Tubes	600-4,000 fpm	NA	$40-200	Accuracy depends on pressure measuring device used.
Manometer (inclined)	0-10 in. H_2O 0-6 in. H_2O	± 1% ± 0.5-1%	$79-355 $125-159	Calibration not required. Must be kept level.
Aneroid Gauges	0-150 in. H_2O 0-100 in. H_2O	± 2% ± 5%	$49-59 $42	Requires periodic calibration.
Micro-manometers	0-2,000 in. H_2O	± 1%	$350-800	Requires battery power and frequent calibration.

Vane anemometers are further subdivided into "rotating vane" and "swinging vane." Rotating vane anemometers incorporate light, wind-driven wheels with recording dials that reflect the speed at which the wheel, or propeller, is rotating when placed in an airstream. The swinging vane anemometer is constructed such that when a case-enclosed vane is placed in an airstream, the vane is deflected by the air movement resulting in a direct readout of air velocity (feet per minute, fpm), proportional to the degree of deflection of the vane.

Thermoanemometers determine air velocity by electronically measuring the cooling effect of air movement on a heated wire or thermocouple. The electronic circuitry provides a direct readout of air velocity in fpm.

Instruments available to measure air pressure include Pitot tubes, manometers (and micro- manometers), and aneroid gauges (e.g., Magnehelics®). A Pitot tube is uniquely constructed with an inner and an outer tube that allows for connection to a differential pressure gauge (i.e., manometers) that will provide a reading for the velocity pressure of the airstream in which the tube is properly oriented. The velocity pressure can then be readily converted to air velocity (fpm).

Manometers range from simple "U-tube" devices to the more sensitive inclined variety. The tubes are filled with water, oil, or mercury (mercury filled manometers are not recommended since they may break or spill and contaminate the area with highly toxic mercury). The levels of the liquids rise or fall depending on the air pressures that the two sides of the manometer are exposed to. The differential pressure can then be read from an attached scale which is then related to an air velocity. The term micromanometer refers to a manometer capable of measuring pressure to three decimal places. The hook gauge is a water-filled laboratory micromanometer that is used as a primary standard for calibrating other manometers. Modern digital micromanometers are quite portable and practical to use for very small pressure measurements in the field. However, they are subject to re-calibration on a regular basis.

Aneroid gauges (Magnehelics®) are small, mechanical gauges that allow the measurement of pressures by reading the needle indication on a dial face.

Table 2 compares the equipment available for evaluating air flow.

Measurement Techniques

An investigator can learn a lot about air flows within a building through the use of chemical smoke. For example, the release of a puff of smoke near a slightly opened door will quickly indicate if the room is under a positive or negative pressure in comparison with the adjacent space. If the smoke transfers out of the room, then the room is under a higher pressure and contaminants generated within that room may migrate to the adjacent space. Likewise, if smoke is released at an outside doorway and is drawn into the building, then that part of the building is under a negative pressure. This is a strong indication that inadequate outside air is being introduced by the HVAC system. When the smoke is released near HVAC supply diffusers, the investigator can tell which way the air is moving, the relative speed, or if it is moving at all. If the smoke stays along the ceiling, then the air is not effectively reaching the occupants. Another useful test is to release smoke in areas that are normally occupied (e.g., at a cubicle or desk) and observe. Dispersal of smoke within a few seconds indicates good air circulation, while smoke that remains still indicates poor circulation.

The measurement of HVAC system air flows can be relatively easy for measurements at grilles and diffusers, but complex for measurements of air flow within the duct work. Within duct work measure-

ments incorporate a time-consuming "Pitot traverse" methodology whereby a number of readings are obtained at precise locations along a cross-section of the duct using a Pitot tube or, at low velocities (less than 400 fpm), thermoanemometer, and then averaged. Methods for making these various types of HVAC system measurements are described in detail in industrial hygiene and mechanical engineering (HVAC) references and texts, and in "HVAC Systems-Testing, Adjusting and Balancing," published by the Sheet Metal and Air-Conditioning Contractors National Association (SMACNA). These methods are also typically found in operating manuals provided by the instrument manufacturers.

Measurements at grilles and diffusers are made most efficiently with flow hoods. The properly sized hood is simply held tightly around the perimeter of the inlet or outlet and the reading taken after allowing a short stabilization time. A swinging vane anemometer or a thermoanemometer may also be used for calculating flows at grilles and vents (following recommended industry practices and manufacturer's instructions). Measuring air flows at diffusers is problematic without a flow hood since the outlet area is not accurately known and the flows are extremely variable along the vanes of the diffuser.

Measurement of air velocities within a room are best accomplished with a thermoanemometer, as it is the only instrument that can accurately detect air velocities as low as 10 fpm. During the cooling season, comfort can be maintained with relatively high air velocities; but in the heating season, air velocities exceeding 30 fpm may be perceived as uncomfortable drafts.

Micromanometers and aneroid gauges are easily used to measure pressure differentials. Generally, a length of tubing is connected to one pressure tap and extended to another area of the building (e.g., under a doorway) and the second pressure tap is kept open to the comparison area in which the investigator is standing. Any pressure differential between the two areas is quickly noted on the gauge or digital readout. Since air flow is towards the lower pressure, contaminant pathways can then be identified.

Note that pressure differences, and therefore air flows, are a function of building layout, HVAC system operating conditions, and outdoor weather conditions. It is important that the conditions encountered at the time of the measurements be documented in order to assist in interpreting the data.

Common Problems

The most common problem encountered in measuring air flows arises when attempting to obtain an accurate flow rate from a diffuser or grille without a flow hood. As mentioned above, the diffuser or grille creates turbulent air flow which is very difficult to assess with point measurements made with an anemometer, and the diffuser/grille reduces the area over which the air is flowing compared to the easily calculated cross-sectional area of the duct work. This makes flow calculations (flow = velocity x area) problematic. The other main issue is in using the measurements to assess IAQ concerns. It is extremely important to realize that the measurements were obtained under certain documented conditions (HVAC operating mode(s), weather conditions, configuration of space). Many times IAQ complaints are sporadic and may be associated with the fluctuating environmental/mechanical conditions that may not arise during the time of the investigation. Finally, it is critical that the instruments used in the investigation should be in proper calibration, and provide the proper sensitivity and operating range to obtain useful data over the range that is likely to be encountered for each parameter (flow, velocity, pressure).

Air Temperature

Reasons for Measurement

Temperature measurements are routinely obtained while performing IAQ assessments in order to assess thermal comfort conditions. The sense of thermal comfort results from an interaction between temperature, relative humidity, air movement, clothing, activity level, and individual physiological differences. Temperature and relative humidity measurements are used as indicators of thermal comfort conditions. ASHRAE Standard 55, "Thermal Environmental Conditions for Human Occupancy", indicates the ranges of temperature and humidity that are likely to be acceptable to most adults in an office or classroom environment. Children can generally be comfortable at temperatures up to 5°F lower due to their higher metabolic rate.

Temperature readings may also be obtained near equipment and exterior surfaces (e.g., photocopiers, large window areas) to identify potential problem areas due to their ability to cause significant heat loss or gain.

The percentage of outdoor air provided by an HVAC system can be estimated using temperature measurements. This technique requires temperature measurements of the outdoor, return, and mixed (supply air before it has been heated or cooled) airstreams. This measurement can then be used to assess HVAC system operation compared to design specifications or to evaluate performance against industry standards (i.e., ASHRAE Standard 62).

Equipment Types

The various types of air temperature measuring instruments include liquid-in-glass thermometers (do not use mercury thermometers which may break and contaminate the area with highly toxic mercury, alcohol is the preferred liquid) and electronic monitors that measure temperature with thermistors, thermocouples, and resistance temperature detectors (RTDs). Electronic temperature monitors provide fast response times, allow for digital read-out, and offer recording capability.

Table 3 compares available types of air temperature monitoring instruments.

Table 3. Comparison of Air Temperature Instruments

Type	Accuracy	Price	Comments
Glass Thermometers			
Pocket	1 Division = 2°	$5-15	
Laboratory Grade	1 Division = 1°	$10-75	
NIST Certified	1 Division = 0.1°	$185-755	
Electronic Monitors			Surface and penetration probes also available.
Thermocouple	0.1-2%	$20-200	
Thermistor	0.3%	$169	
RTD	0.4°F	$250	
Temperature Recorders			
Spring Wound	2% of span	$198-323	
	2% of span	$229-370 (digital readout)	Battery powered.
	1% of span	$484 (digital readout)	
Thermocouple	0.5-1°F	$300-795	Requires power source.

Measurement Techniques

As with all monitoring devices, the manufacturer's instructions should be followed. It is recommended that measurements be taken at the following locations.

- Representative occupant locations (including complaint and general areas)
- Approximately 2 feet from largest window in room
- Expected worst-case areas (near windows, outside walls, equipment, diffusers, etc.)
- Vertical temperature gradients (4 in. above floor and at head level)

These readings should be repeated several times throughout the day since thermal conditions can vary widely with time.

The outdoor air percentage can be calculated after obtaining air temperatures for the outdoor, return, and mixed airstreams within the HVAC system's air handling unit. Some systems are equipped with thermometers and an instrument panel that allows for the direct reading of the temperature of one or more of these airstreams. The percent outdoor air is then calculated using the following equation.

$OA\% = (T_{ret} - T_{mix})/(T_{ret} - T_{o}) \times 100$ where:
OA% = Percent outdoor air
T_{ret} = Return air temperature (°F)
T_{mix} = Mixed air temperature (°F)
T_{o} = Outdoor air temperature (°F)

In addition to assuming that the air handling unit's airstreams are accessible for measurement, there must be at least a several degree temperature difference between the outdoor air and the building's interior.

Common Problems

As noted above, it is important to monitor conditions over time. Many IAQ investigations fail to identify a problem due to the fact that the investigator takes only one set of measurements and assumes that the data represents conditions found in the room/building at all times. Also, one must be careful not to inadvertently assume that worst-case measurements (e.g., those taken near a heat source, or a cold window) are representative of conditions throughout the room/building. Exhaled breath is a potential source of error, especially with hand-held electronic monitors.

Determining percent outdoor air using the temperature measurement technique can be challenging. It is not always obvious how the HVAC system and the air handling units are designed and operated. It can be difficult to ensure you are accessing the proper areas for measurement, and that specific design features (such as an outdoor air preheating coil) are not invalidating your measurements.

It is important that the investigator obtain and review construction drawings and specifications, and meet with building operating staff in order to fully understand how the building is designed and operated.

Relative Humidity

Reasons for Measurement

As described above under "Air Temperature," measurements of relative humidity and temperature are used as indicators of thermal comfort conditions. The optimal comfort ranges for relative humidity are 40-60% in the summer, and 30-50% in the winter. If humidity is maintained at less than 60% throughout the year, this will serve to control microbial growth, another source of IAQ problems. Also, high levels of indoor moisture can damage building and mechanical systems when condensate forms on cold surfaces (windows, uninsulated walls, etc.). Measurements of humidity, then, provide valuable information for controlling comfort, health, and material damage.

Equipment Types

The more commonly used detection methods for quantifying relative humidity levels in IAQ investigations are manual (sling) and motor-driven psychrometers, and hygrometers. Colorimetric detector tubes are not widely used, but can be used as a screening tool. Due to accuracy limitations and difficulties in assessing the length of stain in the indicating portion of the tube, it is difficult to determine relative humidity values within the relatively narrow comfort ranges.

A psychrometer consists of two thermometers mounted side-by-side, with one of the thermometers fitted with a wetted cotton wick around its bulb. As the wetted wick evaporates, the temperature of that thermometer drops until equilibrium is reached. The drier the air, the more moisture evaporates, resulting in lower "wet bulb" temperatures. The manual, or sling, psychrometer is whirled by hand to speed evaporation, while the motorized psychrometer uses a fan to blow air across the wick. Once stabilized, the two thermometers are read and the relative humidity can be interpolated from a psychrometric chart.

Hygrometers are electronic instruments that have digital read-out and data recording, reporting, and charting ability. Both psychrometers and hygrometers provide measurement of temperature, as well as relative humidity.

Some monitors also report readings in dew point temperature. This is the temperature at which condensation of water vapor in the air would occur (if the relative humidity and

Table 4. Comparison of Relative Humidity Devices

Type	Range	Accuracy	Price	Comments
Colorimetric Tubes	5-100% RH	10-15%	$56-72 (10 tubes)	Requires hand pump. Tubes have a 2-year shelf life.
Psychrometers				
Sling	20-120°F	1°F	$37-65	Approx. 1 minute response time.
Motor-driven	10-95% RH	0.3°F	$130-225	2-3 minute response time. Battery operated.
Hygrometers				
Pocket-sized	25-95% RH	5%	$60	All hygrometers are battery powered, and provide temperature read-out. Routine calibration required. Fast response times available.
	0-100% RH	3%	$192	
Meters	20-90% RH	3-5%	$40-100	
	10-95% RH	3%	$180	
	5-98% RH	3%	$300	
	5-99% RH	2%	$435	
	0-100% RH	2%	$720	
Humidity/ Temperature Recorders	15-85% RH	3%	$455-595	Battery powered.
	0-95% RH	2-3%	$599	Requires power source.
	0-100% RH	2%	$775 ($655, RH only)	Fast response. Requires power source and annual laboratory calibration.

barometric pressure remained constant). The relative humidity can be readily obtained from the dew point and room temperature, and most instruments will automatically provide all of these readings.

Table 4 compares these types of relative humidity monitoring devices.

Measurement Techniques

Following the instrument manufacturer's directions, relative humidity measurements can be taken at one representative location (e.g., central or high occupancy area) within each room or HVAC zone (area served by one air handling unit), since humidity does not vary within an area like temperature can. However, like temperature, relative humidity can vary significantly over time. Therefore, it is important to gather data continuously, or at various times over the period of investigation. As with all investigations, it is crucial to document the conditions encountered while obtaining data. Critical factors include outdoor levels (which influence indoor concentrations), HVAC operating conditions, and possible sources of humidity (cooking, pools, locker rooms, etc.).

Common Problems

As with air temperature, the same precautions apply concerning the influence of exhaled breath on hand-held electronic hygrometers, and the monitoring of levels over time. Also, hygrometers tend to drift out of calibration and, if not regularly calibrated, can result in significant error in the data obtained.

Carbon Dioxide

Reasons for Measurement

Carbon dioxide (CO_2) measurements are widely used to assess the adequacy of ventilation provided to an occupied space by an HVAC system. When properly used, CO_2 measurements can be used to calculate the quantity of outdoor air entering the HVAC system for distribution throughout the area served by that system, and the amount of outdoor air that is being effectively provided to building occupants. These measurements can then be used to evaluate HVAC operation compared to design specifications or other presumed operating conditions, and to assess performance against industry standards (i.e., ASHRAE Standard 62).

These measurements are only possible if there are enough occupants in the building to generate CO_2 in exhaled breath in sufficient quantities so that a significant difference can be detected between the CO_2 concentration normally found in outdoor air (350-450 ppm) and that found indoors. For example, if one uses one of the commonly available instruments that provides readout in 50 ppm increments, a difference of 500 ppm would allow measurement of outdoor air at 10% increments and a difference of 250 ppm would allow determination of 20% increments (i.e., 0, 20, 40, 60, 80, or 100% outdoor air). Also, the occupant density must be relatively stable over a period of hours to allow for equilibrium conditions to be reached which is necessary to accurately determine the amount of outdoor air provided per occupant.

Since CO_2 is also a major combustion product, measurements can indicate the potential impact of combustion sources (e.g., motor vehicles, furnaces) on IAQ.

Equipment Types

Carbon dioxide can be measured with direct-reading infrared monitors or Colorimetric indicator tubes. The indicator tubes provide a color change along a sorbent bed, and the length of the stain is proportional to the CO_2 concentration of the air drawn through the tube with a hand pump; or, in the case of passive tubes, the amount of CO_2 diffusing through the tube.

The direct-reading monitors utilize non-dispersive infrared (NDIR) spectrometry techniques to quantify CO_2 levels. Infrared radiation is beamed through the instrument's sampling chamber at a wave length that is absorbed by CO_2 molecules. The monitor's electronics measure the amount of radiation absorbed and provides a direct readout of the corresponding CO_2 concentration.

Table 5 compares these CO_2 monitoring devices.

Measurement Techniques

The Colorimetric indicator tubes used with a hand pump allow for discrete measurements of CO_2 within a room or HVAC zone. The diffusion-type tubes can provide up to an eight-hour time-weighted average concentration. Some investigators have compared indicator tubes with more accurate monitoring devices and have observed extremely wide variations in the tube readings. It is suspected that this is mostly due to the investigator's difficulty in assessing the length of stain in the tube, since the end point for the color change tends to be diffuse.

It is advisable to take one or more readings in control areas to serve as a baseline for comparison. Control points include outdoor air and indoor areas where there are no IAQ complaints. Currently, the Occupational Safety and Health Administration (OSHA) recommends (OSHA Instruction CPL 2-2.20B, the Technical Manual) that indoor CO_2 concentrations not exceed 1,000 parts per million (ppm). This, however, is just a general indicator since spaces with CO_2 concentrations greater than 1,000 ppm do not necessarily indicate that the health of the occupants is being adversely impacted. Likewise, strong or unique contaminant sources can result in problems even if ventilation is adequate to control CO_2 levels to under 1000 ppm.

It takes at least two hours for CO_2 levels to

Table 5. Comparison of Carbon Dioxide Instruments

Type	Range	Accuracy	Response Time	Price	Comments
Colorimetric Tubes					
Active	100-3,000 ppm	10-15%	Approx. 2 min.	$39-42 (10 tubes)	Not generally recommended for IAQ investigations due to perceived inaccuracies and poor precision. Requires hand pump. Tubes have 2-year shelf life.
Passive	62-2,500 ppm	10-15%	Up to 8 hrs.	$53-62 (10 tubes)	No pump required.
Infrared (NDIR) Monitors	0-2,000 ppm 0-5,000 ppm	5% or 50 ppm 2%	Approx. 20 sec. 10 sec. to 90% full scale	$500-595 $2,775	Many NDIR instruments offer capabilities such as data storage, and graphing and reporting software. These options increase the costs above those shown in the table.

reach equilibrium (level off, stop increasing) within a ventilated space. Therefore, it is usually best; if taking individual spot tests, to obtain these measurements in the late morning before the occupants go to lunch, and in the late afternoon before they start leaving for the day. Variable air volume (VAV) HVAC systems present special problems when using CO_2 monitoring techniques since the air flow provided to a space will vary throughout the day, affecting CO_2 concentrations. It is necessary, then, to take a number of measurements, or use continuous monitoring instruments to properly assess conditions.

The above-described techniques may be used with indicator tubes or NDIR monitors to screen for areas that may be underventilated. Remember, it is important to record the conditions under which the data was obtained; such as the number of room occupants, the operating conditions of the HVAC system (especially the outdoor air damper setting), and whether any windows or doors are open.

Using the more accurate NDIR monitors, the outdoor air percentage can be calculated for a given room after obtaining CO_2 measurements in the supply, return, and outdoor air streams. The supply air must be measured before it enters the room and is diluted. This may be accomplished by placing the instrument's probe just inside the supply register/diffuser. The return air may be measured at the face of the return air grille (if more than one return air grille, measure at each, then calculated weighted average based on total return air flow), and the outdoor air in the immediate vicinity of the outdoor air intake for the air handling unit serving the space of concern. The percent of outdoor air is then calculated using the following equation.

$OA\% = (C_{ra} - C_{sa})/(C_{ra} - C_{oa}) \times 100$ where:

OA% = Percent outdoor air

C_{ra} = CO_2 concentration (ppm) at return vent

C_{sa} = CO_2 concentration (ppm) at supply vent

C_{oa} = CO_2 concentration (ppm) in outdoor air

The percentage of outdoor air provided by an air handling unit can be estimated by performing this methodology and calculation for several representative rooms served by the air handler and taking a simple average of the outdoor air percentages obtained. One could also go directly to the air handling unit, as described previously in the Air Temperature section, and obtaining the return, supply and outdoor airstream CO_2 concentrations.

To calculate the lowest amount of outdoor air provided to occupants for comparison to the ASHRAE standard, the outdoor air intake must be at its minimum setting.

After calculating the percentage of outdoor air and obtaining the supply air volume, one can calculate how much total outdoor air is provided to a space, and dividing the total outdoor air, in cfm, by the number of occupants in the space you have calculated cfm of outdoor air/person. This value can then be compared to that recommended by ASHRAE Standard 62. Current classroom and office recommendations are 15 and 20 cfm/person, respectively.

Common Problems

There are a number of problems that may arise when obtaining and interpreting CO_2 data. Since individuals are sources of CO_2 in their exhaled breath (including the investigator), it is important to position the tube/monitor/probe so that it is not influenced by a person's breath. When measuring CO_2 within an occupied room, positioning of the monitor is also crucial so that it measures CO_2 concentrations that are representative of the entire occupied area. For example, it should not be located directly beneath a supply vent, and it should not be placed far from the areas of the room that have the highest occupant densities.

To aid in the interpretation of the data, it is important to record conditions encountered during the measurement period, including number of room occupants. When responding to a complaint, it is not unusual for the conditions to be substantially different during the investigation versus those at the time of the complaint. Critical items to consider include HVAC operating parameters, number of people present, the influence/presence of specific contaminant sources, and whether doors and windows were opened or closed.

Also, if sufficient time was not allowed for CO_2 concentrations to reach equilibrium, then calculations of amounts of outdoor air provided to the space will be overstated. As mentioned above, VAV systems are problematic for assessing amounts of outdoor air reaching a space since they do not allow time for equilibrium conditions to be achieved before changing the volume of air provided.

Finally, if the CO_2 concentrations in a space are unusually high, then it is important to check for the potential leakage of combustion gases into the space. Sources could include a cracked heat exchanger in the furnace, emissions from a gas range, or back-drafting flue gases.

Quality Assurance/Quality Control

It is important that school facility personnel consider, and provide for, the elements of a good IAQ quality assurance/quality control (QA/QC) program before establishing in-house sampling and monitoring capabilities. It is recommended that a written QA Plan be established that addresses, at a minimum, the following:

- Responsible person – a single, adequately trained individual should be responsible for the program
- Equipment – the types of equipment must be identified and provision must be made for routine maintenance and calibration
- Standard operating procedures (SOPs) – each instrument should have written SOPs that detail sampling, calibration, and maintenance methods and schedules

Before undertaking an investigation or sampling/monitoring program, it is important that the approach has been well thought out, so that resource usage is optimized and quality data obtained. The best way to do this is to develop a sampling plan, or strategy. The strategy summarizes the reason for the sampling and describes the approach selected. The approach will identify how measurements will be obtained (instruments, sampling techniques), the sampling locations, and the dates and times of the sampling.

The following factors affecting data quality should be considered when selecting sampling instruments and methods:

- Accuracy and Precision – will the errors inherent in the method still allow useful data to be collected?
- Interferences – are there interfering substances or other factors present that may invalidate the data?
- Detection Limits – is the technique sensitive enough to provide data at the levels of interest?

Finally, after collecting the data, it is important to evaluate its validity. The investigator should assess the data against the following criteria:

- Proper operation of instruments over the sampling/monitoring period
- Acceptable pre- and post-calibration results

- Duplicate samples/readings within acceptable ranges
- Reasons identified for extreme data points
- Calculations performed properly
- Results consistent with other measurements and expectations.

IAQ conditions should only be assessed using data in which the investigator has confidence.

Conclusions

Many of the IAQ problems that arise in facilities have been attributed to the provision of inadequate quantities of outdoor air by the HVAC system to occupants, or to complaints of thermal discomfort. This bulletin has provided a review of the instruments and measuring techniques that can be utilized by school facility personnel to assess these problems. With a good understanding of the dynamics of the key IAQ parameters discussed in this bulletin, and a modest investment in monitoring equipment, school facilities staff can provide quick, cost-effective responses to IAQ complaints and establish programs that can identify potential IAQ problem areas before they reach a crisis stage. While the instruments and techniques presented here are effective in evaluating the general adequacy of ventilation systems and identifying pollutant pathways, it is beyond the scope of this bulletin, and the service capabilities of most facility staffs, to perform in-depth evaluations of HVAC mechanical systems or to sample for a wide variety of chemical and biological pollutants. If the initial response by school personnel is not sufficient to identify and rectify the problem, then it is appropriate to bring in a qualified consultant who is capable of providing more in-depth, technical evaluations.

A complete set of the instruments and devices described in this bulletin can be purchased for less than $1,500, or up to more than $5,000. A set of equipment in the lower cost range (chemical smoke, thermoanemometer, micromanometer, sling psychrometer, and NDIR CO_2 monitor) can be quite effective for assessing many IAQ conditions. The more expensive instruments are characterized by somewhat greater sensitivities; faster response; and extensive data storage, retrieval, and reporting options.

The more expensive instruments also provide school personnel with the advantage of unattended operation. The presence of an IAQ investigator in a classroom can create significant classroom disturbances and distractions.

In addition to minimizing classroom disruption, these units offer excellent graphic displays that document the variations in the parameters measured over time. This aids in data interpretation and allows for a more complete understanding of the situation being assessed.

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